arktos (2018) 4:25
https://doi.org/10.1007/s41063-018-0059-6

ORIGINAL ARTICLE

Pre-mid-Frasnian angular unconformity on Kotel'ny Island (New Siberian Islands archipelago): evidence of mid-Paleozoic deformation in the Russian High Arctic

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Received: 15 November 2017 / Accepted: 13 August 2018

Abstract
We present detailed structural studies which reveal for the first time the existence of an angular unconformity at the base of the Middle Frasnian deposits across the western part of Kotel'ny Island (New Siberian Islands, Russian High Arctic). Pre-Mesozoic convergent structures are characterized by sublatitudinal folds and south-verging thrusts. Based on the age of the rock units above and below the unconformity, the age of the deformation event can be described as post-Givetian but pre-mid-Frasnian. Based on the vergence direction of thrusts deforming pre-Frasnian deposits on Kotel'ny Island, shortening occurred from north to south (in the present day coordinates). The small scale of the structures suggests that this part of the New Siberian Islands formed a distal part of an orogenic belt in the Middle Paleozoic. The angular unconformity described on Kotel'ny Island can be tentatively correlated with the Ellesmerian Orogeny. However, due to a paucity of detailed geological data from the neighboring broad Arctic continental shelves, a precise correlation with known tectonic events of the circum-Arctic cannot be achieved. The subsequent Mesozoic tectonic structures with NW-trending folds and faults were superimposed on pre-existing Paleozoic and older structures. Thus, the data presented here provide additional constraints on the Paleozoic geodynamic affinity of the New Siberian Islands and provide a regional link to other Arctic regions, aiding future tectonic reconstructions of the circum-Arctic.

Keywords Arctic · New Siberian Islands · Kotel'ny Island · Late Devonian deformation · Angular unconformity · Structural geology

Introduction

The New Siberian Islands (NSI) archipelago is located at the boundary between the Laptev and East Siberian seas and comprises several islands varying in size and geological structure. The Paleozoic geodynamic affinity of the NSI is ambiguous. It is believed that they either formed part of the Siberian [4, 25] or Arctida paleocontinents [47], have an affinity with Arctic Alaska [7], were a discrete geological terrane [30, 31], or share an affinity with Laurentia or Baltica [5, 11–15]. At the present time, the NSI are mainly considered as part of the New Siberian–Chukotka, New Siberian–Chukotka–North Alaska, Chukotka-Alaska, or Arctic Alaska–Chukotka microcontinents (superterranes, microplates), or the Arctida and Bennett-Barovia terranes [e.g., 16, 28, 32–34, 43, 45 and references therein].

Kotel'ny Island is located in the western part of the archipelago and is the largest island within the NSI. It is mainly composed of deformed Paleozoic deposits (Fig. 1a–c), whereas Mesozoic and Cenozoic rocks are only locally preserved within synclines and around the periphery of the island [20–22]. Previous studies suggest that the Paleozoic–Mesozoic rocks of Kotel'ny Island were only deformed into NW-striking folds in the Late Mesozoic, associated with

This article was selected from the third Circum-Arctic Structural Event workshop which was held in Hannover (Germany) in March 2017.

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Published online: 04 September 2018

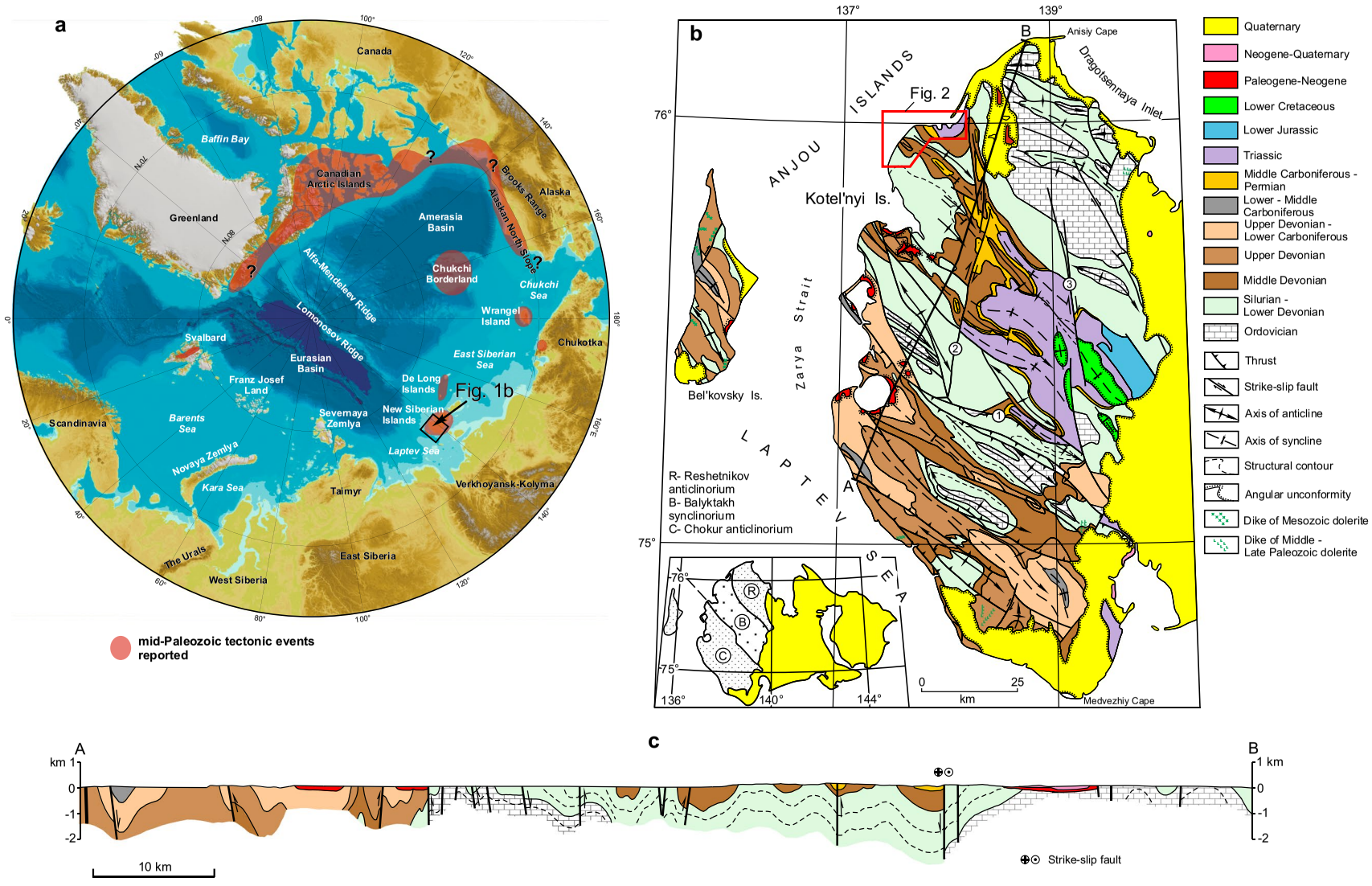


Fig. 1 **a** Map showing areas affected by mid-Paleozoic deformations across the Arctic realm (modified from [42]). **b** Structural map of the western Kotel'ny Island with location of study area. Faults: 1—Mikhailov thrust, 2—Upper-Balyktakh dextral strike-slip, 3—Tuor-Yurekh dextral strike-slip fault. Shown in the lower left corner is a tectonic zonation sketch map (modified from [36]). R—Reshetnikov anticlinorium, B—Balyktakh synclinorium, C—Chokur anticlinorium. **c** Geological section **A**–**B** across the western part of Kotel'ny Island (modified from [20])

reverse faults and SW and NE directed thrusts [e.g., 36]. Several angular unconformities have been identified across the island, with well-studied angular unconformities at the base of the Aptian in the central part of the island and at the base of the Paleogene [20]. The latter unconformity is related to extension associated with opening of the Eurasian Basin. By contrast, the Paleozoic history of deformation on Kotel'ny Island is poorly understood. An angular unconformity at the base of the Lower Carboniferous strata has been identified in the southeast of Kotel'ny Island, where Lower Carboniferous rocks rest on Ordovician, Silurian and Devonian strata, but has been poorly studied to date [20]. Here, we present the results of a study with the aim of better understanding the pre-Mesozoic deformation and tectonic history of Kotel'ny Island, aiding correlations to the circum-Arctic and providing new constraints on the Paleozoic geodynamic affinity of the NSI.

We carried out a detailed study of coastal exposures in the northwestern part of the island with the aim to elucidate relationships between the exposed stratigraphic units. Here we present new data on the structural relationship between Lower–Middle and Upper Devonian strata across the north western part of Kotel'ny Island.

Stratigraphy of the northwestern Kotel'ny Island

On the northwestern coast of Kotel'ny Island (Fig. 2a), the oldest exposed Paleozoic rocks are Lower Devonian in age. The Lochkovian deposits consist of alternating marls, dolomites and limy shales (Pshenitsyn Fm., [3, 23]) (Fig. 2b). The contact with overlying rocks is not exposed. Pragian–Lower Emsian deposits comprise massive bituminous limestones with numerous corals (Basykh-Karga Fm., 165–300 m). Uppermost Lower Emsian–Upper Emsian strata are represented by gray to black limestones with rare thin interbeds of limy shales (Shlyupka Fm., 300 m). The Middle Devonian (Eifelian–Givetian) strata unconformably overlie Lower Devonian and Silurian deposits in the northern part of the island, but are conformable in its southern part [20]. Across northwestern Kotel'ny Island, these strata are mostly represented by sedimentary carbonate breccias. Layered micritic limestones with thickness reaching a few tens of meters locally occur within succession (Sokolov Fm., 500–600 m). The facies transition between breccias and layered limestones can be observed in a few exposures.

The Frasnian deposits (Nerpalakh Fm.) across northwestern Kotel'ny Island overlie Middle Devonian carbonates with evidence for significant erosion at the base [20]. The Nerpalakh Formation comprises 52 m of alternating varicolored green and red clays and siltstones, with subordinate beds of marls, bioclastic limestones and sandstones with rare

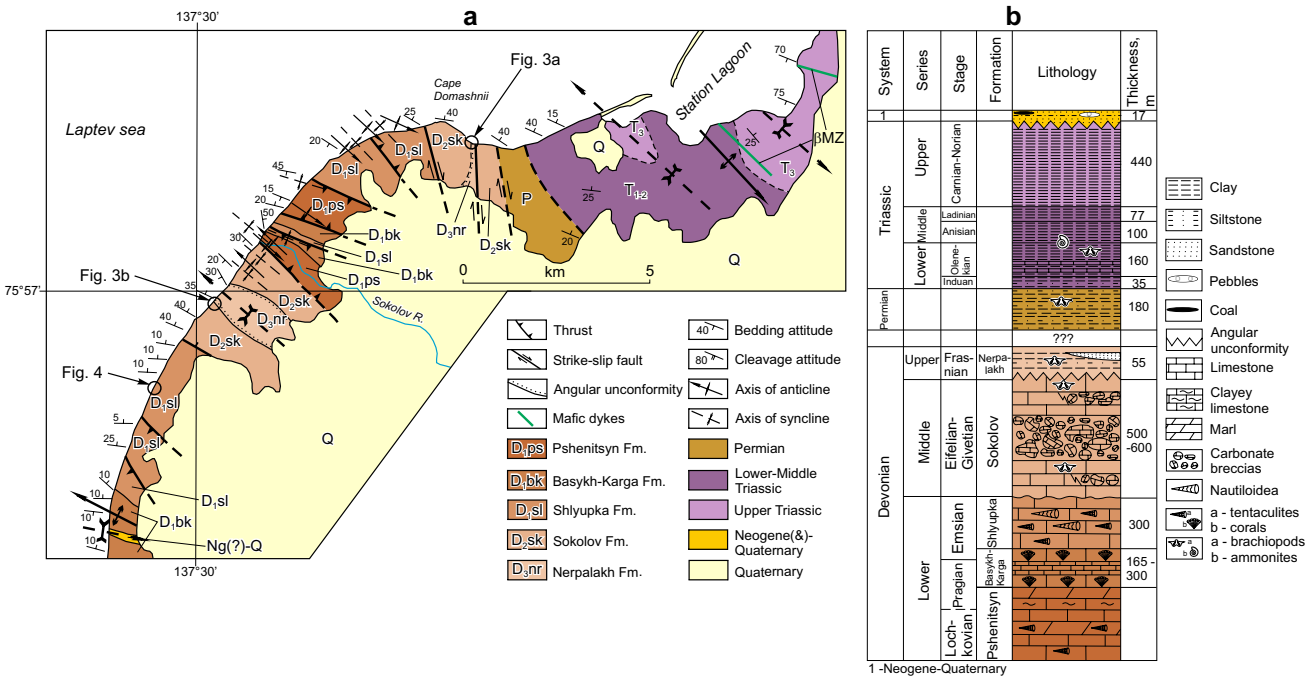
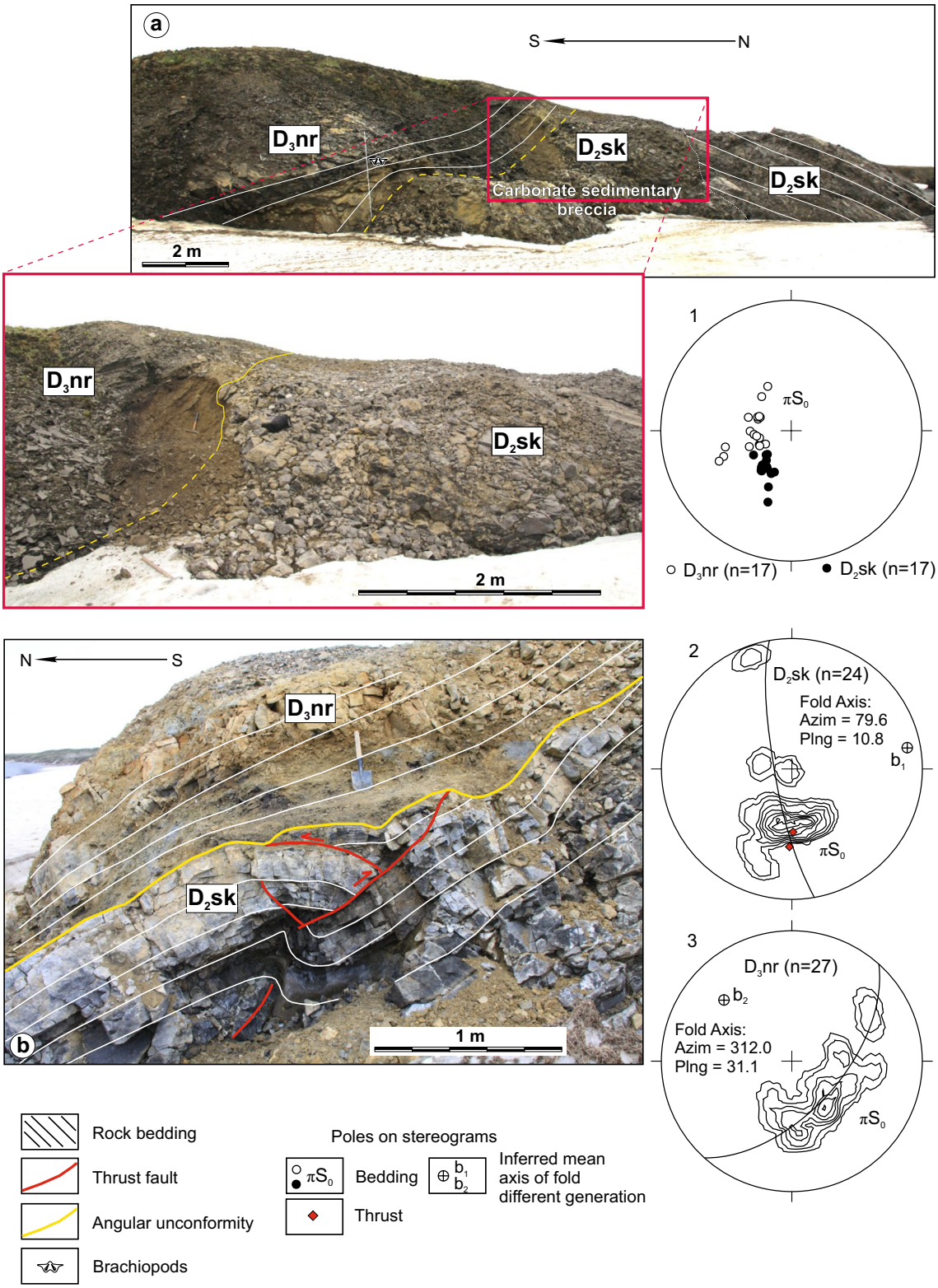


Fig. 2 Geological map of northwestern Kotel'ny Island (**a**) and stratigraphic column (**b**). For location see Fig. 1



brachiopods in the northwestern part of the island. The erosional topography at the base of the Nerpalakh Formation is infilled by gravelly and pebbly conglomerates comprising clasts of underlying limestones of the Sokolov Formation [20]. In the southwestern part of the island, Frasnian deposits comprise alternating grayish clays and siltstones with subordinate layers of sandstone and limestone. Kos'ko et al. [20] suggest that the thickness of Frasnian deposits in the

◂**Fig. 3** Angular unconformity (yellow line) between Sokolov Fm (D_2sk) (Middle Devonian) and overlying Frasnian Nerpalakh Formation (D_3nr): **a** near Station Lagoon and **b** in the mouth of Sokolov River, northwestern Kotel'ny Island. Stereo plot 1 shows distribution of bedding poles in exposure near Station Lagoon. Black circles show bedding poles of the rocks of Sokolov Formation and white circles those of Nerpalakh Formation. Stereo plots 2 and 3 show distribution of bedding poles in an exposure in the mouth of Sokolov River. Stereo plot 2 shows bedding poles of Sokolov Formation rocks directly beneath unconformity (red rhombs are poles of thrust surfaces shown in **b**). Stereo plot 3 shows bedding poles of Nerpalakh Formation rocks deformed into open syncline in whose limb the described unconformity is located (see Fig. 2). Circled crosses are poles of constructed fold axes, *n* number of measurements. Equal-area projections, lower hemisphere. For location see Fig. 2

southern part of the island varies from 1 to 7.7 km, however, this great thickness is likely to be an overestimation of the true stratigraphic thickness due to repetition of the stratigraphy by faulting and folding [13].

The Permian (undivided) succession is represented by 180 m of siltstones and shales with subordinate beds of silty sandstones in the northwest of Kotel'ny Island. Contacts with both overlying and underlying rocks are not exposed here.

The Triassic deposits (undivided) comprise clays and black shales with thin beds of limestones, dolomites and siltstones. The total thickness here does not exceed few 100 m (Fig. 2).

Mid-Paleozoic angular unconformity

Across northwestern Kotel'ny Island evidence for the Late Devonian angular unconformity was found in two exposures on the Laptev Sea shore near Station Lagoon (Cape Domashnii) and near the mouth of the Sokolov River (Figs. 2, 3).

The first exposure locates 5 km west of Station Lagoon in the Cape Domashnii area, where Middle Devonian sedimentary carbonate breccia and layered limestones of the Sokolov Formation dip to the NNE at 30–40° (Figs. 2, 3a, stereogram 1). Givetian ostracodes and brachiopods *Ilmenia ex gr. hians* (Buch) have been described from the limestones [20]. Givetian limestones are overlain by thin-platy limestones. The overlying limestones were earlier described as Carboniferous in age [20]. However, our findings of brachiopods—*Desquamatia ex gr. tenuisulcata* (Wen.) and *Mucrospirifer ex gr. novosibiricus* (Toll) suggest a mid-Frasnian age. These brachiopods have been described from the Nerpalakh Formation (Frasnian) from other localities across Kotel'ny Island [20], and therefore we attribute host limestones to the Nerpalakh Formation.

There are clays with carbonate pebbles filling in erosional topography at the base of the Nerpalakh Formation. Its thickness varies from 1 to 3 cm in the northern part of the exposure to as much as 15–20 cm in the southern part. Dip azimuths of the Nerpalakh Formation rocks are different from those of the underlying Sokolov Formation. Mid-Frasnian limestones are inclined to the NE, W and SW, and are deformed into a meso-scale anticline which occurs on the northeastern limb of a larger open syncline of WNW strike (Fig. 3a, stereogram 1). The trend of the fold is similar to that of the Late Mesozoic folds, which are widespread in the region. No slickensides are observed at the contact and between the Sokolov and Nerpalakh Formations, nor any other evidence of fault tectonics. These characteristics suggest the presence of an angular unconformity between the Sokolov and Nerpalakh formations.

The second exposure is located 2 km southwest of the Sokolov River mouth. Here, thick platy dark-gray limestones of the Sokolov Formation are deformed into small folds of ENE trend and cut by a south-directed thrust (Fig. 3b, stereogram 2). According to Kos'ko et al. [20], limestones in this outcrop contain Givetian ostracodes and brachiopods *Ilmenia ex gr. hians* (Buch). They are overlain by thin-platy limestones of the Nerpalakh Formation comprising brachiopods *Uchtospirifer* sp., "*Camarotoechia*" *ex gr. livonica Buch., Desquamatia ex gr. tenuisulcata* (Wen.), *Mucrospirifer ex gr. novosibiricus* (Toll) and pelecypods *Actinopteria (?)* sp., *Actinopteria cf. wurmii Roemer* [20], indicative of their mid-Frasnian age. Interlayered siltstones, varicolored clays and thin-platy limestones occur upsection. A gray clay band 10–45 cm wide with fragments and rare pebbles of limestone occurs at the base of the lower limestone bed. The Nerpalakh Formation overlies the deeply eroded irregular surface of the deformed limestones of the Sokolov Formation, and in the southern part of the exposure its base cuts erosively down into bedding of the Sokolov Formation (Fig. 3b). No slickensides were found on the top surface of the Sokolov Formation, suggesting that this contact does not represent a fault plane. Deposits of the Nerpalakh Formation comprise the southwestern limb of a large open syncline with an axis plunging to the northwest at ~ 10° (Figs. 2, 3b, stereogram 3), subparallel to the trend of abundant Mesozoic folds throughout the island. Therefore, the character of the contact between the Sokolov and Nerpalakh Formations, along with the difference in structural patterns of deformation between them, indicates the presence of an angular unconformity.

A few kilometers to the south from the second exposure, limestones of the Shlyupka Formation (Emsian) are deformed into tight to isoclinal folds striking W–E and cut by south–southwest-directed thrusts (Figs. 2, 4). The Shlyupka Formation displays similar structural patterns to those observed in the Givetian limestones of the Sokolov Formation at Cape Domashnii. These similarities in structural style provide additional evidence that pre-Frasnian strata have a different structural style compared to overlying Paleozoic and Mesozoic succession across the study area, and were

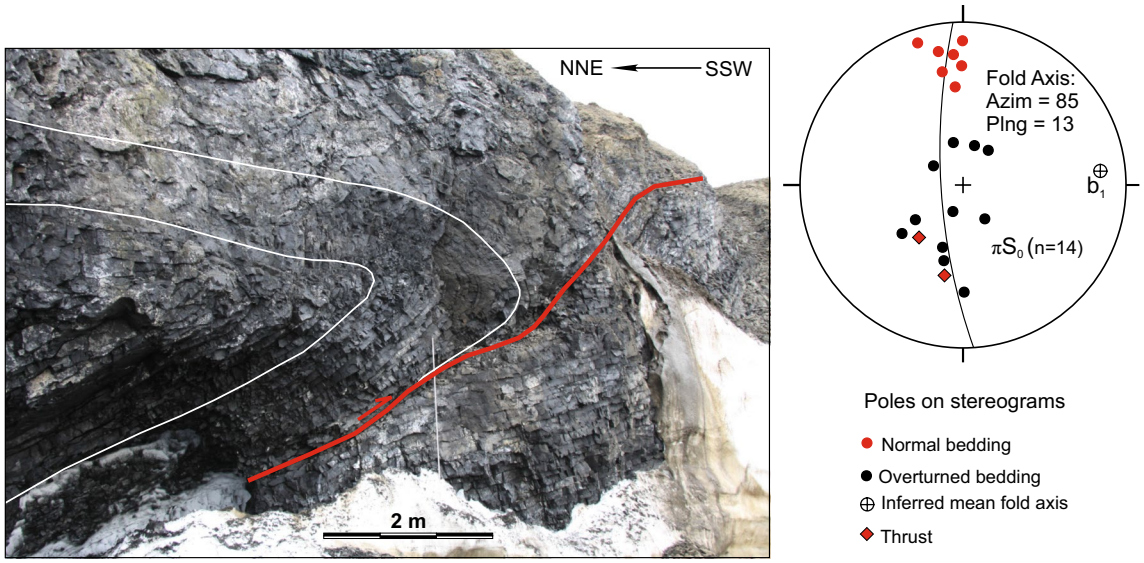


Fig. 4 Tight fold overturned to SSW in Lower Devonian carbonates (Shlyupka Formation). Stereo plot shows orientation of bedding poles in the exposure shown in the photo (circles) and of poles of thrust surface (rhombs). Equal-area projection, lower hemisphere. For location see Fig. 2

therefore involved in an older tectonic event which the younger Paleozoic and Mesozoic formations above the inferred unconformity did not experience.

Discussion and conclusion

We report evidence for an angular unconformity at the base of the Middle Frasnian succession, representing an episode of pre-Mesozoic convergent deformation with sublatitudinal folds and south-directed thrusts on western Kotel'ny Island. Based on the ages of rock units above and below the unconformity, as inferred from macrofossil biostratigraphy, the age of this deformation event can be described as post-Givetian but pre-mid-Frasnian. The Mesozoic tectonic event with NW-trending folds and faults was superimposed on these older structures.

During the Late Devonian, the northern part of Siberia was affected by extensional as opposed to contractional deformation. The Early Frasnian basalts and normal faults described from the northeastern part of Siberian craton (Lena River Delta area) [36] caused by widespread Middle Paleozoic rifting known across the Siberia continent [e.g., 10, 40]. The Kotel'ny Island is known to be correlated with Arctic Alaska based on faunal association and lithostratigraphy [e.g., 7]. According to detrital zircon provenance study Upper Devonian–Lower Carboniferous deposits from Kotel'ny and Bel'kovsky islands yield detrital zircon populations that are consistent with the age of magmatic and metamorphic rocks within the Grenvillian–Sveconorwegian, Timanian, and Caledonian orogenic belts, but not with the Siberian craton [13, 14]. Therefore, our data support models claiming a non-Siberian affinity of the NSI. According to these models, Kotel'ny Island represents a part of the Arctic Alaska–Chukotka microcontinent (e.g., [6]).

Based on the tectonic transport direction of thrusts deforming pre-Frasnian deposits on Kotel'ny Island, shortening occurred from north to south (in the present day coordinates) at the boundary between the Middle and early Late Devonian successions. The small scale of the structures suggests this part of the NSI formed a distal part of an orogenic belt in this interval.

There is abundant evidence for circum-Arctic mid-Paleozoic convergent deformation. Ellesmerian tectonism (Late Devonian to Early Carboniferous) is known in NW Canada (Yukon and adjacent areas) [e.g., 26], the Canadian Arctic Islands [e.g., 17, 18, 39], north Greenland [e.g., 44], NW Chukotka [e.g., 19, 27], and Svalbard (Svalbardian Orogeny) [e.g., 24, 29, 37, 38, 42]. Mid-Paleozoic deformation events have been described from the De Long Islands [41], Wrangel Island [46] and Chukchi Borderland [35]. The Early Devonian to earliest Middle Devonian Romanzof Orogeny occurred across northwestern Yukon, northeastern Alaska and the North Slope of Alaska [e.g., 1, 26]. However, convergent tectonic events of a more precise post-Givetian to pre-mid-Frasnian age have thus far not been described from the circum-Arctic, which hampers a correlation of the inferred tectonic event on Kotel'ny Island with the known mid-Paleozoic tectonic events in the region.

However, there are vast portions of the Arctic continental shelves which are submerged beneath the Arctic Ocean, have not been drilled, and have been very poorly studied by modern geophysical methods, limiting our understanding of their Paleozoic tectonic history. Furthermore, Middle–Upper

Devonian rocks of the Canadian Arctic contain detrital zircons with a Timanian provenance signal (550–650 Ma) and which are exotic for northern Laurentia [2]. As a result, it has been proposed that a terrane or microcontinent collided with northern Laurentia (modern coordinates) in the Middle Devonian, providing the source for the exotic provenance signal ("Crockerland" [e.g., 8, 9]). Therefore, Anfinson et al. [2] suggest that "Crockerland" was accreted to the northern margin of the Canadian Arctic and Greenland during a multi-stage collision from the Early Devonian to early Mississippian time, resulting in the Ellesmerian Orogeny.

The post-Givetian and pre-mid-Frasnian angular unconformity we describe here from Kotel'ny Island could therefore be tentatively correlated with one of the phases of the Ellesmerian Orogeny. However, precise correlation cannot be achieved at present due to the lack of drilling and geophysical data from the neighboring submerged continental shelves. The new data presented here provide additional constraints on the affinity of the NSI, however, additional geological data from the adjacent Arctic shelves are urgently required to construct more definitive correlations between tectonic events on Kotel'ny Island and those of the wider Arctic realm.

Acknowledgements The study was partly supported by project no. 0381-2016-0001 of the Diamond and Precious Metal Geology Institute, and project 53 of program 44P of the Presidium of the Russian Academy of Sciences. Structural data processing and interpretation were supported by Grant no. 17-17-01171 by the Russian Science Foundation. Fieldwork was performed in the framework of the joint project of TGS Nopec Co., Clapton Research and Saint-Petersburg University Centre for Geology LLC. We thank two anonymous reviewers for detailed critical analysis and comments that significantly improved the manuscript.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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